

A COMPARISON OF THE METHODS FOR
TESTING INSULATING MATERIALS FOR
POWER FACTOR AND DIELECTRIC
CONSTANT AT 1000 CYCLES

By
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DISSERTATION

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VITA

Louis Wendell Marks, son of Ferdinand Godfrey Marks and Sue Blanche Marks, was born in Baltimore, Md., on June 23, 1908.

He received his elementary and secondary education in the Baltimore City Public Schools, graduating from the Baltimore Polytechnic Institute in June, 1926. In October of that year he matriculated at The Johns Hopkins University as a student in Electrical Engineering and in June, 1930, received the degree of Bachelor of Engineering, graduating with honor.

In October, 1930, he returned to The Johns Hopkins University for a period of three years as a Graduate Student in the School of Engineering. His principal subject was Electrical Engineering and his first and second subordinates were Physics and Mathematics, respectively. During the course of graduate instruction he studied under Prof. J. B. Whitehead, Prof. W. B. Kouwenhoven, and Dr. F. Hamburger of the Department of Electrical Engineering; Prof. A. H. Pfund and Dr. G. H. Dieke of the Department of Physics; Prof. A. Cohen and Prof. F. D. Murnaghan of the Department of Mathematics.

During the summer months he was employed by the Chesapeake and Potomac Telephone Co. of Washington, D. C., and the General Electric Co. of Schenectady, N. Y. His membership in professional and honorary societies include: Member, Tau Beta Pi; Member, Sigma Xi; and Associate Member, A.I.E.E.



A COMPARISON OF THE METHODS FOR TESTING INSULATING MATERIALS FOR POWER FACTOR AND DIELECTRIC CONSTANT AT 1000 CYCLES

By W. B. KOUWENHOVEN¹ AND L. W. MARKS²

SYNOPSIS

This paper discusses the series resistance and the parallel resistance bridges which have been proposed as A.S.T.M. methods for the measurement of dielectric characteristics at 1000 cycles. The possibility of using the balanced Schering bridge for the same purpose was also investigated. These methods were studied both from the theoretical and practical viewpoints. Measurements were made upon a number of samples by all three methods and the results compared. The authors recommend the use of the substitution method and a Wagner grounded bridge. They point out that the balanced Schering bridge offers a single piece of apparatus that may be satisfactorily used over a range of frequency from 25 to 1000 cycles.

In the Tentative Method D 150 - 32 T (1)³ developed by Committee D-9 on Electrical Insulating Materials of the American Society for Testing Materials three methods are set forth for the measurement of the dielectric constant and the power factor of insulating materials at 1000 cycles. The three methods are:

1. The inductance bridge of Rosa and Grover(2).
2. The series resistance bridge of Max Wien(3).
3. The parallel resistance bridge of Rosa(4).

This paper deals with a study of these three methods and also discusses the possibilities of using the balanced Schering bridge as an alternate method of measuring the constants of insulating materials.

In this study the inductance bridge was eliminated at an early stage because the tentative method calls for specimens whose capacitance varies from 1000 to 3500 $\mu\text{mf.}$ for use in this bridge, while in

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³ The boldface numbers in parentheses refer to the reports and papers given in the list of references appended to this paper, see p. 18.

the other two bridge methods specimens of only one-tenth of this size are required. Therefore, the inductance bridge was eliminated from the comparison.

The investigation covered a wide field which may be divided into the following parts:

1. The series resistance, the parallel resistance and the Schering bridges were studied from a theoretical viewpoint to determine their inherent errors. This study resulted in the decision to recommend the parallel substitution method as the most satisfactory plan of operation for all three bridges.

2. Their shielding was investigated.

3. The sensitivities of the bridges were compared.

4. Where possible each bridge was checked for accuracy against a low power factor standard.

5. The bridges were compared with and without the use of the Wagner ground.

6. A number of specimens covering a wide range of insulating materials were tested both with and without guard electrodes.

7. The effect of the spacing of guard electrodes was measured as a function of specimen thickness.

Before commencing the theoretical study of the bridges from the standpoint of residual errors, effects of stray capacitances, etc., it was necessary to consider the type and test conditions of specimens which were to be tested. The specimens consisted of flat disks of insulating material to which lead foil electrodes could be applied to opposite surfaces. It is well known that the constants of a given sample of insulation vary with the temperature and that if check results are to be secured, the temperature must be held constant. In order to meet this requirement the specimens were placed in a box in which the temperature and humidity were maintained constant. In such a constant temperature container the electrode surfaces on the specimen are within fairly close proximity to the walls of the box and the resulting stray capacitance will introduce an error in the results unless it is taken into account or eliminated. This stray capacitance and its elimination were considered in the analysis of the bridges.

SERIES RESISTANCE BRIDGE

The series resistance bridge shown in Fig. 1 is one of the proposed standard methods. In the commercial bridge of this type the ratio arms R_1 and R_2 are each 5000 ohms, C_s is a standard air capacitor with a range of 50 to 1500 $\mu\mu\text{f.}$, C_1 is an air capacitor of at least 1000

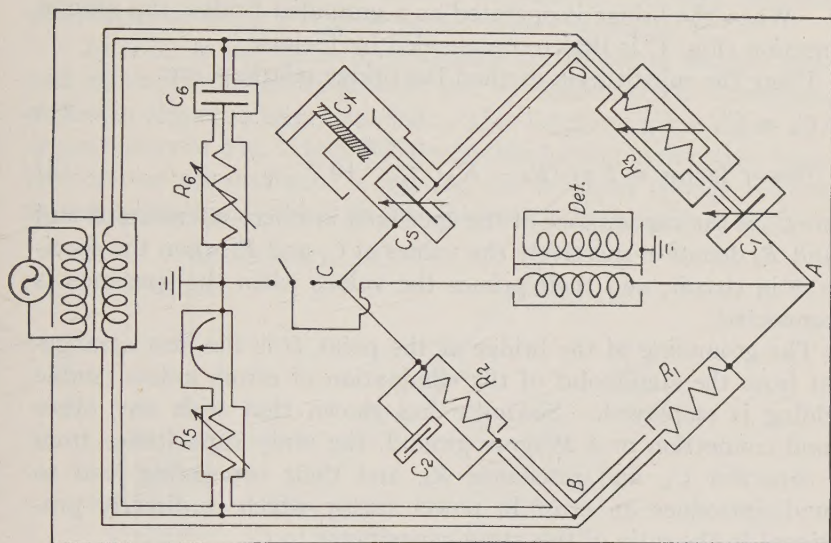


FIG. 2.—Double Shielded Series Resistance Bridge.

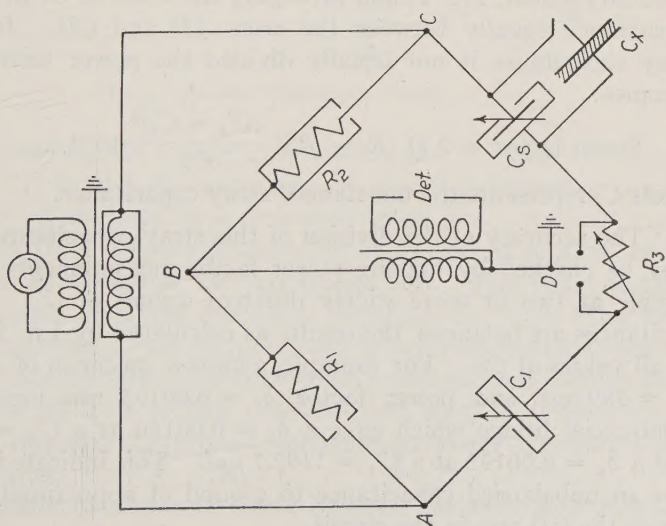


FIG. 1.—Series Resistance Bridge.

$\mu\mu\text{f.}$ The specimen is represented by the capacitance C_x . The resistance R_3 is variable in 1.0-ohm steps. The resistances R_1 , R_2 and R_3 and the input and detector transformers are enclosed in a metal box. When the bridge is operated as a grounded bridge, the ground connection (Fig. 1) is that recommended by Field(5).

Using the substitution method the bridge relations are:

$$C_x = C'_s - C_s \dots \dots \dots (1)$$

$$\text{Power factor} = 2 \pi f (R_3 - R'_3) \frac{(C'_s)^2}{(C_x)} 10^{-12} \dots \dots \dots (2)$$

where C_x is the capacitance of the specimen in micro-microfarads and C_s and R_3 denote respectively the values of C_s and R_3 when the specimen is in circuit, and their primes the values when the specimen is disconnected.

The grounding of the bridge at the point D is the best arrangement from the standpoint of the elimination of errors unless double shielding is employed. Siskind(6) has shown that with any other ground connection or a Wagner ground, the stray capacitance from the capacitor C_1 , and resistance R_3 , and their connecting lead to ground, introduce an error in power factor which is directly proportional to the ratio of this stray capacitance to C_1 .

Another source of error in this bridge is the capacitance to ground of the secondary of the input transformer and of the leads connecting the capacitors to the corners of the bridge. In a one to one bridge the effect of this stray capacitance may be eliminated by splitting the secondary shield, Fig. 1, and arranging the leads so as to divide this capacitance equally between the arms AD and CD . In case this stray capacitance is not equally divided the power factor equation becomes:

$$\text{Power factor} = 2 \pi f (R_3 - R'_3) \frac{(C'_s \pm C_3)^2}{C_x} 10^{-12} \dots \dots \dots (3)$$

where C_3 represents the unbalanced stray capacitance.

The accuracy of the division of this stray capacitance to ground may be checked by making power factor measurements of a given sample at two or more widely different values of C'_s . If the capacitances are balanced, the results as calculated by Eq. 2 will check at all values of C'_s . For example, a known specimen of capacitance $C_x = 289 \mu\mu\text{f.}$ and power factor $\delta_x = 0.00193$ was measured in a commercial bridge which gave a $\delta_x = 0.00186$ at a $C'_s = 360.5 \mu\mu\text{f.}$ and a $\delta_x = 0.00192$ at a $C'_s = 1192.7 \mu\mu\text{f.}$ This indicated that there was an unbalanced capacitance to ground of approximately $5.5 \mu\mu\text{f.}$ across the CD arm in the circuit.

An error, which is common to all of the grounded bridges, is that caused by the stray capacitance from the high voltage electrode of the specimen to ground as already mentioned. It may be readily eliminated by using a Wagner ground with the bridge.

In order to use the series resistance bridge with a Wagner ground and eliminate the errors pointed out by Siskind⁽⁶⁾, the arrangement shown in Fig. 2 is recommended. This bridge is a conjugate of the arrangement of Fig. 1 and it is preferable to that connection because the load on the oscillator is reduced and a higher voltage is applied to the specimen. In this double shielded series resistance bridge the

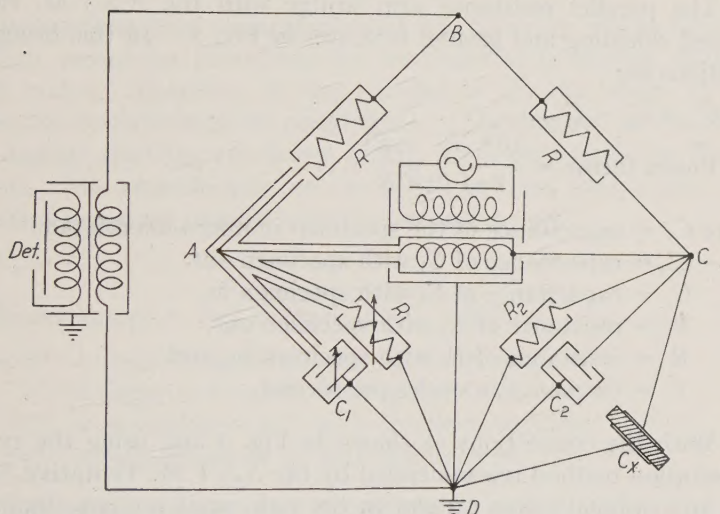


FIG. 3.—Parallel Resistance Bridge.

ratio arms R_1 and R_2 , the capacitors C_1 and C_2 , and the Wagner ground components C_3 , R_3 and R_4 , as well as the input and detector transformers, were all enclosed in a grounded metal box. A small fixed mica capacitor C_2 is connected across the ratio arm R_2 so as to keep the resistance R_3 always in the AD bridge arm. The value of this capacitor depends upon the quality of capacitor C_1 . The capacitor C_1 and the resistance R_3 are each enclosed in separate grounded boxes and the capacitance to ground of their common lead is kept a minimum. The resistance R_3 is at a high potential and its dial handles were brought out through the ground shielding to avoid the effects of body capacitance.

The insertion of a ground shield between the resistance R_3 and capacitor C_1 as used by Sommerman⁽⁷⁾ eliminates the stray capac-

itance between the *A* and *D* corners of the bridge and their effect upon the results.

The use of the Wagner ground makes it possible to completely shield the high voltage lead to the specimen and eliminate the capacitance of the leads from the results. It also eliminates the stray capacitance from the high voltage electrode to the specimen container and permits the use of guard electrodes on the specimen if desired.

PARALLEL RESISTANCE ARM BRIDGE

The parallel resistance arm bridge with the A.S.T.M. recommended shielding and ground is shown in Fig. 3. In this bridge the equations are:

$$C_x = C_s - C'_s \dots \dots \dots (4)$$

$$\text{Power factor} = \frac{10^{12} (R' - R)}{2 \pi f C_x R' R} \dots \dots \dots (5)$$

where C_x = capacitance of the specimen in micro-microfarad,

C'_s = capacitance of C_1 with specimen out,

C_s = capacitance of C_1 with specimen in,

R' = resistance of R_1 with specimen out,

R = resistance of R_1 with specimen in, and

f = frequency in cycles per second.

With the connections as shown in Fig. 3 and using the type of substitution method recommended by the A.S.T.M. Tentative Standard, any residual errors present in the ratio arms are not eliminated. However, in a one to one bridge with accurately balanced residuals their effect is negligible. There is also an error introduced by the stray capacitance from the high side of the specimen to ground. This error may be eliminated by the use of the Wagner ground as explained under the series resistance bridge.

In its commercial form this bridge has the following circuit constants. The resistances R_1 and R_2 are each 10,000 ohms and R_1 is a six-dial resistance box having steps varying from 0.01 ohm to 1000 ohms. The ratio arms are each 1000 ohms and C_2 has a value of 200 $\mu\mu\text{f}$. In the commercial form of the bridge, a Wagner ground is permanently connected across the source. This arrangement of placing the relatively low resistances of the Wagner ground in parallel with the capacitors noticeably decreases the sensitivity of the bridge when it is used as a grounded bridge. It is desirable to provide means of readily disconnecting the Wagner ground not only in this bridge

but also in all commercial bridges because occasions may arise where it is necessary to operate the bridge grounded.

In using the commercial bridge with specimens of low power factor, the difference between the two values of R_1 with the specimen in and with the specimen out is small. This difference may be increased by the use of 100,000-ohm resistances in R_1 and R_2 and their use increases the difference $R' - R$ one hundred times for a given specimen. Large resistance units in R_1 and R_2 materially increase the sensitivity of the bridge in the range of frequencies used.

BALANCED SCHERING BRIDGE

It has long been recognized that the Schering bridge offers an excellent means for measuring the constants of insulating materials at 60 cycles. Therefore, it was decided to try the bridge at 1000 cycles and to determine its possibilities. The diagram of the bridge used and its shielding are shown in Fig. 4 complete with the Wagner ground. The variable arms are the C_1 , R_1 arm and the C_4 arm. The equations using the parallel substitution method are:

$$C_x = C'_s - C_s \dots \dots \dots (6)$$

$$\text{Power factor} = 2 \pi f R_1 (C_1 - C'_1) \frac{C'_s}{C_x} 10^{-12} \dots \dots \dots (7)$$

where C'_s = capacitance of C_4 with specimen out,

C_s = capacitance of C_4 with specimen in,

C'_1 = capacitance of C_1 with specimen out, and

C_1 = capacitance of C_1 with specimen in.

This bridge was operated successfully at both 60 and 1000 cycles. The resistances R_1 and R_2 were each 5000 ohms. The capacitor C_2 was a mica capacitor of 250 $\mu\mu\text{f}$. The capacitors C_1 and C_4 were variable, each with a range of 50 to 1500 $\mu\mu\text{f}$. For maximum sensitivity C_3 should have a capacitance about 1.5 times the value of C_x . In the Wagner ground the resistance R_5 had a maximum value of 1100 ohms and R_6 11,110 ohms. A small slide wire resistance of a few ohms range was provided for fine adjustment in the R_5 circuit. When the bridge was used at 1000 cycles the Wagner ground mica capacitor C_6 had a value of 0.005 μf . For 60-cycle work an additional mica capacitor of 0.03 μf . was connected in the circuit. The bridge was shielded and was completely enclosed in a grounded metal box.

The balanced Schering bridge of Fig. 4 proved very simple to operate, including the balancing of the Wagner ground. The conjugate arrangement suggested by Siskind⁽⁶⁾ was tried. It gave accurate results, but required considerably more time and skill to balance

than the bridge of Fig. 4. At 1000 cycles the bridge was supplied with power from the oscillator and the amplifier with telephones was used in the detector circuit, described later. At 60 cycles the supply was furnished by a sine wave generator and the detector was either a vibration galvanometer or a Leeds and Northrup alternating current needle galvanometer separately excited by means of a phase shifting transformer using the method developed by Kouwenhoven

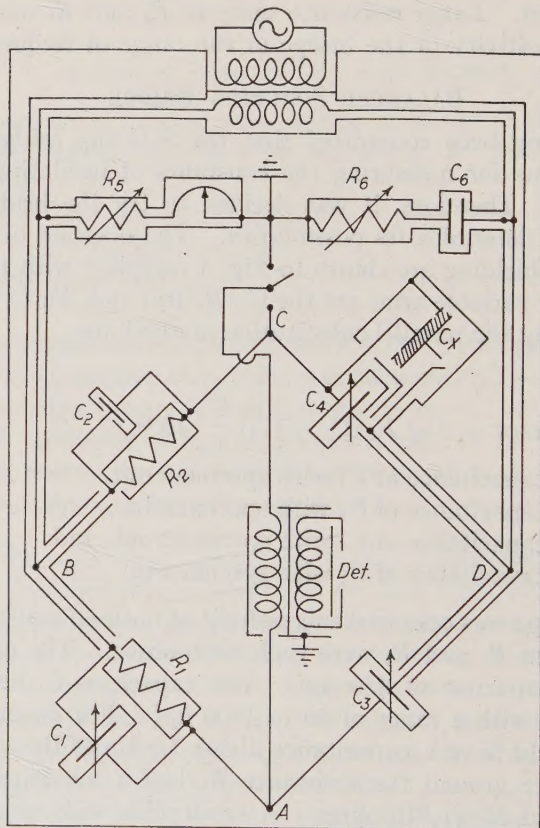


FIG. 4.—Balanced Schering Bridge.

and Banos⁽⁸⁾. This latter method permits separate balancing of the power factor and capacitance, but where it is used in conjunction with an amplifier in the detector circuit, the operation of the amplifier should be maintained constant.

The Schering bridge may be also used as a solidly grounded bridge, but unless guard electrodes with guard balancing equipment⁽⁹⁾ are used on the specimen, it possesses many of the disadvantages of the other solidly grounded bridges.

Using the parallel substitution method in the balanced Schering bridge eliminates all residual errors and with the Wagner ground the effects of capacitance from the specimen electrodes to ground are not present. This bridge gave satisfactory results at both 60 and 1000 cycles. It may also be operated at somewhat higher frequencies if desired. It had ample sensitivity at both frequencies.

OSCILLATOR AND DETECTOR

The A.S.T.M. Tentative Method D 150 - 32 T gives one the choice of several types of 1000-cycle sources of supply. For this work the vacuum tube oscillator was chosen, using the Hartley⁽⁹⁾ circuit and a No. 210 tube as the oscillator. The output of the oscillator was fed into a simple class A amplifier employing a No. 250 tube. The output of the plate circuit of this tube could be connected to either a tuned air core variable coupling transformer or to a special iron core transformer. In both transformers primary and secondary were separated by shields. With these arrangements a supply of energy at 1000 cycles was available over a voltage range of 5 to 300 volts. The frequency of the oscillator was adjusted to 1000 cycles using a frequency sensitive Wien bridge and was checked by an oscillograph. It was found to be constant to within two cycles over the entire range of load and to be independent of normal changes in plate and filament voltages. The detector circuit consisted of a Western Electric type 104AE shielded output transformer feeding into a two- or three-stage resistance capacity coupled amplifier. The output of the last stage of this amplifier was fed through a one to one transformer and the telephones were attached to the secondary.

SENSITIVITY COMPARISON

There are several methods available for determining the sensitivity of bridges. In this work the series resistance bridge and the parallel resistance bridge were available in commercial form, and the balanced Schering bridge was built up as shown in Fig. 4 from laboratory equipment.

In measuring the relative sensitivity of these bridges, they were balanced using a value of capacitor C' , of 300 $\mu\mu\text{f}$. Then assuming that the average size of specimen has a capacitance of 200 $\mu\mu\text{f}$, the change in the power factor balancing arm corresponding to a change in the power factor of the specimen of 0.0008 was calculated. The power factor balancing unit was then upset by this amount and the resulting noise in the telephones reduced to extinction by an audibility meter. Then the power factor balance was restored and the

capacitance balance upset by $0.6 \mu\text{mf.}$ in C' , and the test repeated. In the case of the two commercial bridges, 30 volts at 1000 cycles was applied to their input terminals, and in the Schering bridge the same voltage was applied directly to the B and D bridge terminals. In all tests the amplification of the detector output was held constant. The results of a set of typical sensitivity measurements using all three bridges solidly grounded and with Wagner grounds disconnected are given below. A high reading of the audibility meter indicates high sensitivity:

BRIDGE	SETTING OF AUDIBILITY METER	
	FOR POWER FACTOR UNBALANCE	FOR CAPACITANCE UNBALANCE
Commercial series resistance bridge.....	400	1300
Commercial parallel resistance bridge.....	29	74
Laboratory Schering bridge.....	200	650

In the commercial parallel-resistance bridge the Wagner ground is solidly connected across the source so that when used as a grounded bridge it becomes a shunting impedance on the R_1 and R_2 arms. Using the bridge as it is designed commercially, and grounded, its sensitivity fell so that for the given power factor unbalance the audibility meter read 11 and for the capacitance unbalance 29. Using it with Wagner ground disconnected and 100,000-ohm boxes in R_1 and R_2 instead of the 10,000-ohm units furnished in the commercial bridge, its sensitivity reading was 150 for power factor upset and 500 for capacitance upset. Experience in operation and other sensitivity tests confirm the above results.

ACCURACY STUDY OF THE BRIDGES

In the Engineering Laboratories at The Johns Hopkins University there is available the Low Power Factor Standard of Kouwenhoven and Berberich⁽¹⁰⁾. Briefly this consists of a shielded and guarded loss-free capacitor connected in series with ideally shielded resistors. In this investigation two resistors were used, giving at 1000 cycles power factors of 0.03322 and 0.00325, respectively. The capacitance of the low power factor standard is $517.5 \mu\text{mf.}$, which is larger than that of the specimens, but well within the range of the three bridges.

Only bridges employing the Wagner ground may be readily checked against the low power factor standard. A special guard circuit with complicated shielding is required for checking a grounded bridge. The double shielded series resistance bridge of Fig. 2, the commercial parallel resistance bridge of Fig. 3 and the balanced Schering bridge of Fig. 4, each equipped with its Wagner ground, were

checked against the power factor standard. In these tests the same source of power and detector arrangement were used. The results are given in Table I.

The results show good accuracy to within the sensitivity of the individual bridges. The series resistance and Schering bridges with a sensitivity of the order of 1×10^{-5} in power factor checked the standard in every test to within better than 3×10^{-5} in power factor. In the commercial parallel resistance bridge a variation of 0.01 ohm in R_1 corresponds to a change in power factor of 3×10^{-5} at this value of C_x . This small change in R_1 is difficult to detect at 1000

TABLE I.—RELATION OF MEASURED POWER FACTOR TO STANDARD.

BRIDGE	STANDARD	MEASURED	MEASURED CAPACITANCE
	POWER FACTOR	POWER FACTOR	
Series resistance (Fig. 2).....	0.03322	0.03322	517.6
	0.00325	0.00322	517.2
Parallel resistance (Fig. 3), 10,000 ohm.....	0.03322	0.03315	516.9
	0.00325	0.00314	517.2
	0.00325	0.00332	517.8
Parallel resistance (Fig. 3), 100,000 ohm.....	0.03322	0.03320	516.1
	0.00325	0.00322	516.2
Schering Fig. 4	0.03322	0.03320	517.5
	0.00325	0.003245	517.7

TABLE II.—ELECTRICAL PROPERTIES OF TYPICAL SPECIMENS.

Specimen	Material	Form	Thickness, in.	Dielectric Constant	Power Factor	Hours to Reach Final Value
L-1.....	Laminated bakelite....	Round	0.192	5.93	0.0368	6
L-2.....	Laminated bakelite....	Square	0.192	5.94	0.0367	8
C-1.....	Clear yellow bakelite....	Square	0.1768	7.01	0.0566	8
C-25.....	Clear blue bakelite....	Square	0.1913	3.93	0.00696	..
X-150-2.....	Fine fabric.....	Square	0.0638	4.73	0.0200	over 48
Z.....	Paper laminated.....	Square	0.1279	5.38	0.0248	6
ZM-264.....	Black bakelite.....	Square	0.1188	6.55	0.1175	8

cycles. The differences between the true and measured values given in Table I are directly attributable to the lower sensitivity of this bridge. Using 100,000-ohm resistance boxes in the R_1 and R_2 arms of this bridge, an excellent check was obtained with the power factor standard.

SPECIMENS

Specimens were employed in the further comparison of the bridges. They were used in the study of the solidly grounded and Wagner grounded bridges, in the comparison of the results on guarded and unguarded specimens, and on the effects of guard spacings. The electrodes were of lead foil and on specimens without guards were

4.5 in. in diameter. On guarded specimens the high voltage electrode was a 6-in. round or square disk, depending upon the sample, and the low voltage electrodes 4.5 in. in diameter. Table II gives a list of typical specimens referred to in this paper and their electrical properties as measured with guard electrodes at 30 C. and 60 per cent relative humidity.

The importance of maintaining constant temperature and humidity of a specimen during a test has already been referred to. A box 7.5 in. square by 5.5 in. high was used to hold the specimens. This box was placed in an oil bath and provided with thermostatic control which maintained the temperature constant to within ± 0.1 C. The humidity within the box was held at a constant value by the use of a concentrated ammonium nitrate solution. The constant temperature-humidity chamber is shown in Fig. 5.

In Fig. 5 may also be seen the spring and weight contacts found convenient and satisfactory for the rapid interchange of specimens. The brass weight, about 1 lb., was sufficient to depress the spring and at the same time insure good contact with the guard shield. The latter was removed when measuring specimens with equal electrodes.

Tests were made on the same specimens, using No. 30 B. & S. leads soldered to both upper and lower electrodes and then replacing the leads with the weight and spring contact of Fig. 5. The results are given below on specimen L-1 as measured in two of the bridges after being held at constant temperature and humidity for over 24 hours:

Bridge	Bridge Ground	Contacts	C_x , $\mu\mu\text{f.}$	Dielectric Constant	Power Factor
Commercial series resistance.....	Solid.....	Fine wire.....	115.0	6.17	0.0350
Commercial series resistance.....	Solid.....	Weight and spring.....	115.9	6.22	0.0348
Schering.....	Wagner.....	Fine wire.....	110.5	5.93	0.0368
Schering.....	Wagner.....	Weight and spring.....	110.5	5.93	0.0368

Both electrodes on the specimen were 4.5 in. in diameter. The tests on the solidly grounded commercial series resistance bridge, where the measured capacitance includes the capacitance of the high voltage electrode to ground, show that the weight increased this capacitance by nearly 1 $\mu\mu\text{f.}$ When a Wagner grounded bridge was used, the results show clearly that the capacitance of the specimen and its power factor are exactly the same for both types of connection.

The importance of maintaining specimens at constant temperature cannot be overemphasized. For example, specimen C_1 at 20 C. had a power factor of 0.035 and a dielectric constant of 6.64; at 30 C. these values had increased to 0.056 and 7.01, respectively. This also

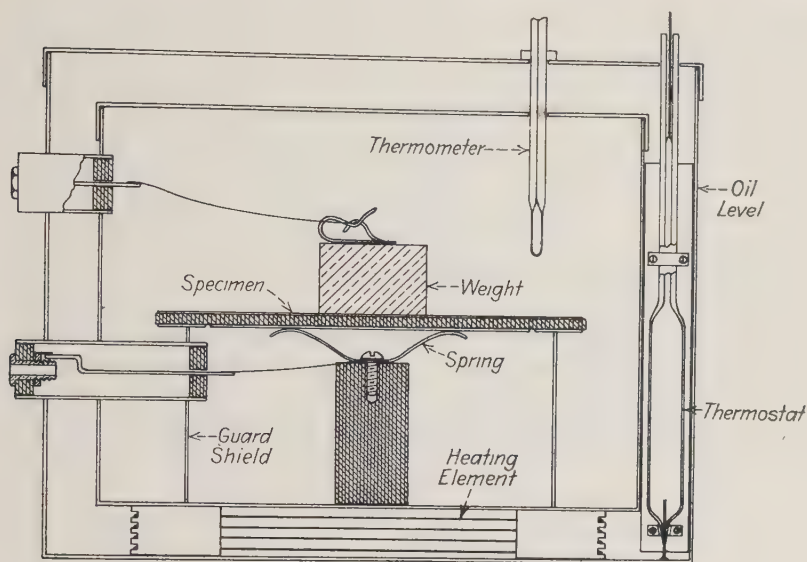


FIG. 5.—Specimen Container.

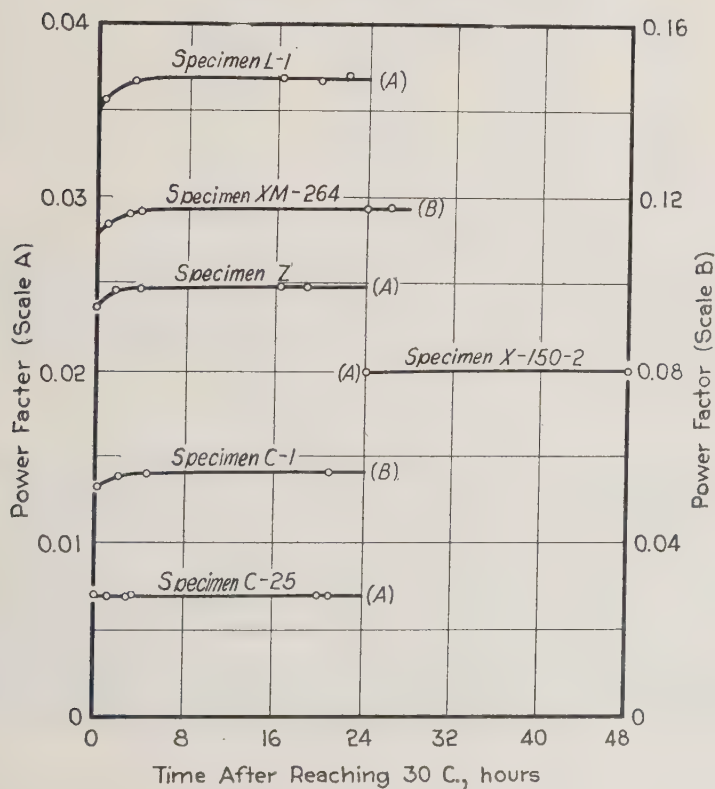


FIG. 6.—Time to Reach Steady Conditions. Room temperature 21 to 23 C.

brings out the desirability of measuring specimens throughout their working temperature range.

The A.S.T.M. Tentative Method D 150 - 32 T provides that a specimen shall be held at constant temperature and humidity for 48 hours before testing. With this requirement in view, a series of measurements was made on a number of specimens at intervals after the thermometer indicated constant temperature, and the results are given in Fig. 6. It may be seen that the change in power factor of the specimens measured was negligible after 6 or 8 hours at constant temperature.

It is recommended that in practice, readings be taken at intervals after a specimen has been placed in a constant temperature container,

TABLE III.—DATA FOR SPECIMENS TESTED IN THE CONSTANT TEMPERATURE BOX.

Specimen	Bridge	Type of Grounding	$C_x - C_e$	Dielectric Constant, K	Power Factor	Percentage Difference in K
L-1.....	Series resistance....	Solid.....	115.0	6.17	0.0350	+4.6
	Parallel resistance....	Solid.....	115.0	6.17	0.0360	+4.6
	Schering.....	Solid.....	114.7	6.15	0.03538	+4.2
	Parallel resistance....	Wagner.....	109.5	5.885	0.03675	0
	Schering.....	Wagner.....	109.8	5.900	0.03690	0
C-1.....	Series resistance....	Solid.....	146.2	7.23	0.0525	+3.4
	Parallel resistance....	Solid.....	144.5	7.15	0.0521	+2.3
	Schering.....	Solid.....	145.2	7.18	0.0507	+2.7
	Schering.....	Wagner.....	141.2	6.99	0.0555	0
C-25.....	Parallel resistance....	Solid.....	76.7	4.07	0.0071	+3.5
	Schering.....	Solid.....	76.5	4.06	0.00682	+3.3
	Schering.....	Wagner.....	74.2	3.93	0.00696	0

and that a power factor - time curve be plotted. This will be helpful in determining when the specimen has reached equilibrium.

It is also interesting to note that over the range of 25 to 300 volts at 1000 cycles, no differences were found in the constants of the materials tested. Hartshorn⁽¹¹⁾ obtained similar results on sheets of varnished cloth.

THE WAGNER GROUND

The capacitance from the high voltage electrode to ground causes an error in the solidly grounded bridge. It may be eliminated by the use of the Wagner ground as already mentioned. In Table III are given data for three specimens, L-1, C-1 and C-25 which were tested in the constant temperature box, using fine wires soldered to their 4.5-in. electrodes. In the case of specimen C-25 using the Wagner ground, guard electrodes were employed. The measured value of the specimen capacitance C_x was corrected, using the edge correction C_e of Hoch⁽¹²⁾ and the dielectric constant of the specimen

calculated from the corrected value. A study of Table III shows clearly that the dielectric constant is too high for specimens measured in any one of the three bridges when solidly grounded. The calculated power factor is also in error in such cases. When, however, the Wagner ground was used, this stray capacitance was eliminated and the results are much more accurate.

GUARD ELECTRODES

A number of experiments were made using guard electrodes to check the edge correction and the effects of surface leakage at 60 per cent relative humidity. In Table IV are given typical results of measurements on four specimens of varying thickness. All of these were measured after having been held at constant temperature for at least 20 hours. Measurements were made using equal 4.5-in. diameter electrodes on both surfaces, and using the same sample with

TABLE IV.—TESTS MADE WITH AND WITHOUT GUARDS ON SCHERING BRIDGE WITH WAGNER GROUND.

Specimen	Electrodes	C_x , $\mu\text{mf.}$	C_e , $\mu\text{mf.}$	Dielectric Constant	Power Factor	Thickness, in.
C-25.....	Guards.....	74.2		3.93	0.00699	0.1913
	Equal.....	76.7	3.6	3.91	0.00705	
X-150-2.....	Guards.....	267.2		4.74	0.01975	0.0633
	Equal.....	268.7	4.1	4.73	0.01987	
L-1.....	Guards.....	112.9		5.95	0.03685	0.192
	Equal.....	115.3	4.8	5.93	0.0368	
C-1.....	Guards.....	142.9		7.01	0.0566	0.1763
	Equal.....	146.4	5.2	6.99	0.0555	

a 6-in. electrode on one side and a 4.5-in. electrode with guard ring opposite. The spacing between the guard ring and electrode was small. In Table IV C_x is the measured value of specimen capacitance. In calculating the dielectric constant with guard ring, the effective radius of the 4.5-in. diameter electrode must be increased by one-half of the spacing between the guard ring and the electrode. With equal electrodes the edge correction C_e was used.

The results of Table IV show that over the rather wide range of thickness and dielectric constant, Hoch's correction gives good results, and that surface leakage was negligible.

In applying guards to a specimen, care must be taken to keep the spacing between the guard and the electrode small, otherwise errors will be introduced by the non-uniform flux distribution in this space, which is considered as uniform in calculating the equivalent air capacitance. A series of tests was made on specimens of different

thickness varying the spacing between the guard ring and the main electrode from 0.025 to 0.2 in. The dielectric constant and the power factor were calculated for each spacing and specimen and the results plotted as a function of guard spacing. As the spacing increased, there was a falling off in dielectric constant as calculated which was more rapid the thinner the specimen. There was also a slight change in the calculated power factor. These curves were extrapolated to zero guard spacing and the resulting dielectric constant and power factor considered as the true constants of the material.

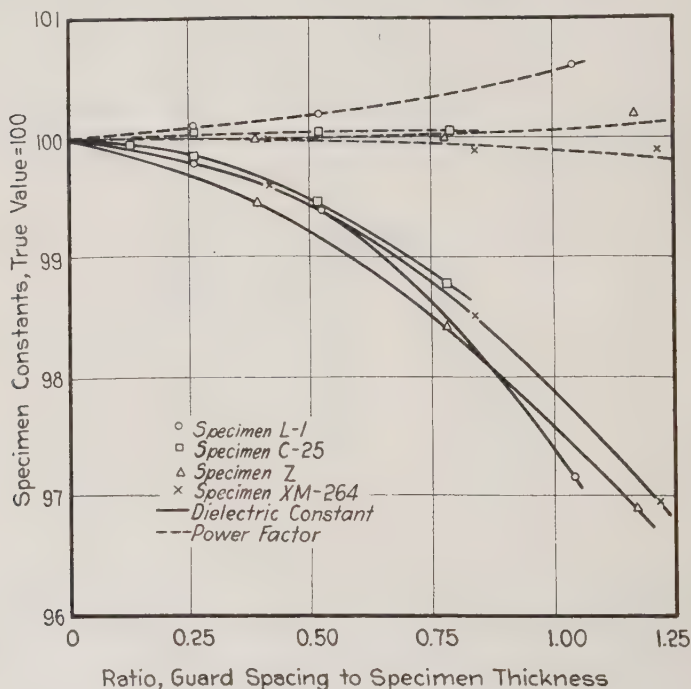


FIG. 7.—Effect of Guard Spacing.

In Fig. 7 the results for four specimens are plotted with the ratio of guard spacing to specimen thickness as abscissa and with the constants of the specimens reduced to the same scale as ordinates, the true values being taken as 100 for each specimen. A study of Fig. 7 shows that when the guard spacing was one half the specimen thickness, the calculated dielectric constant was about 0.6 per cent low, while the maximum error in power factor was less than 0.25 per cent for any of the four specimens. When the guard spacing was one-fourth of the thickness, the error in dielectric constant was 0.25 per cent and negligible in power factor.

The A.S.T.M. Standards call for a minimum specimen thickness of 0.1 in. This means that the guard ring spacing should be 0.025 in., which can be readily obtained provided the lead foil is cut with a pair of dividers.

Using the guard electrodes properly spaced or equal electrodes accurately centered gave good results at 1000 cycles. Experience indicated that it was somewhat simpler to use guard electrodes than accurately to center equal electrodes.

REPRODUCIBILITY OF RESULTS

There are so many variables and sources of error that enter into the measurement of dielectric constant and power factor of specimens that it is interesting to determine to what extent results are reproducible.

TABLE V.—MEASUREMENTS MADE IN THE SCHERING BRIDGE.

SPECIMEN	DATE	HOURS AT 30 C.	POWER FACTOR	DIELECTRIC CONSTANT
L-1.....	12/7/32.....	23	0.0368	5.93
	12/16/32.....	22	0.0368	5.93
	3/2/33.....	144	0.0369	5.90
L-2.....	12/1/32.....	21	0.0367	5.94
X-150-2.....	2/1/33.....	48	0.02005	4.73
	2/8/33.....	226	0.02005	4.74
	3/27/33.....	18	0.01975	4.73

The results of a number of measurements made at different times on various specimens in the Schering bridge are given in Table V. Specimen L-2 was cut from the same sheet as specimen L-1. From a study of the data in Table V and the results of other tests it was found that the results were reproducible to within 1 per cent in dielectric constant and to better than 5 per cent in power factor.

SUMMARY

1. The use of the substitution method of measurement eliminates inherent bridge errors.

2. The results obtained with solidly grounded bridges as recommended by the A.S.T.M. method are subject to errors due mainly to stray capacitances to ground.

3. The use of the Wagner ground eliminates errors arising from stray capacitances to ground, and permits guard electrodes to be used without complications in the bridge circuit. Means, however, should be provided for readily disconnecting the Wagner ground.

4. The series resistance bridge has ample sensitivity, but as a grounded bridge its accuracy is impaired by stray capacitances. A double shielded series resistance bridge allows the adoption of a Wagner ground and gives excellent accuracy.

5. The sensitivity of the parallel resistance bridge at 1000 cycles is increased by the use of larger resistances in the R_1 and R_2 arms. This is especially desirable when the bridge is used with small specimens of low power factor.

6. The balanced Schering bridge equipped with a Wagner ground provides in a single bridge a wide range of frequency operation, and would serve equally well for measurements at both 60 and 1000 cycles. It has ample sensitivity and accuracy.

7. Guard electrodes may be readily applied to specimens when using bridges employing the Wagner ground. With the proper guard spacing they eliminate edge corrections, and do not require a centering operation.

8. Equal centered electrodes, using the proper edge corrections, give results consistent with those obtained with guard electrodes. The edge corrections proposed by the Society were checked very closely considering the wide differences in specimens and conditions. The effect of surface leakage at 1000 cycles and 60 per cent relative humidity was found to be negligible.

9. It is important that specimens be maintained at constant temperature while testing until equilibrium is reached and that their constants should be measured throughout the working range of temperature.

RECOMMENDATIONS

The following practices are recommended for the measurement of dielectric constant and power factor of specimens at 1000 cycles:

1. The use of the substitution method.
2. The use of a Wagner grounded bridge provided with means for readily disconnecting the ground if desired.
3. The use of the balanced Schering bridge, equipped with Wagner ground, as the standard test method at both 60 and 1000 cycles.

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